Pressures and Depths of Crystallization of the FAMOUS Region Magmas

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By

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Abstract

The FAMOUS region is between the Mid-Atlantic Ridge and the rift valley which is < 3,000-21,000 ±6,000 years old. This study used analyses of basalt glass from the FAMOUS region. The depth of crystallization is calculated from estimated pressures. To do so we filtered the data by removing any glasses with anomalous chemical compositions or samples that had estimated pressures that were obviously incorrect. The results for 65 glasses indicate that FAMOUS region magmas crystallize over a relatively wide range of pressures from 0 - 228.5MPa, corresponding to depths of 0-8.04 km with an average of 1.42km. Information of the depths of chambers and pressures of crystallization is important for understanding magma evolution, magma plumbing systems, and predicting volcanic activity.

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Introduction

The primary goal of this study is to establish depth of the magma chambers in the French American Mid-Ocean Undersea Study (FAMOUS) region of the Mid Atlantic Ridge through understanding the geochemical variations of glass samples. There are many reasons that knowing the depth of magma chambers is important. First, information on magma chamber depth aids in understanding tectonic events and may lead to more accurate predictions of volcanic eruptions (Marti and Folch, 2009). Second, knowledge of the depths of chambers provides constraints on models for magma evolution, because melt compositions differ as a function of pressure (O'Hara, 1968; Thy, 1991; Grove et al. 1992; Yang et al. 1996). Third, the distribution of magma in the crust provides an understanding of the thermal gradient which affects variations in seismic velocity and density in the crust (Kelley et al. 2005). Finally, the proportions and locations of magma chambers are crucial to understand mechanisms of crustal accretion, differentiation, and sources for geothermal energy (Pan and Batiza, 2002, 2003).

For the purpose of this study, 65 glass analyses from the FAMOUS region were compiled. From these analyses, pressures of crystallization were calculated based on comparison with melt compositions lying along the pressure dependent olivine-plagioclase-clinopyroxene coetectic as described by Yang et al. (1996). The estimates of the pressures of crystallization of the FAMOUS magmas were used to determine the depths of magma chambers.

First, quantitative pressure which ranged from 0.1 -228.5 MPa were obtained using the compositions of glasses. Second, pressures were determined using glasses from the FAMOUS area (latitude 36° 44' - 36° 52’, longitude 30° 70'-33° 99') which allows us to estimate the depth of magma chambers to be approximately 0-8.04 km with an average of 1.42km in that region.

Geologic Setting

The 1978 Axial Mid-Atlantic Ridge expedition surveyed and sampled the MAR in the FAMOUS and AMAR rift valleys by submersible. The purpose for the expedition was to learn more about the magmatic and tectonic processes that are directly related to the driving forces that cause drive tectonics and sea floor spreading. Exploration of mid-ocean ridges by submersible, deep-sea cameras, and other devices provides clear evidence of the effects of recent magmatic activity along these divergent plate boundaries. The samples gathered from the expedition were dredged from outcrops by the three submersibles: Alvin, Archimede, and Cyana at water depths of about 2600 meters. During the expedition, 534 rock samples were recovered, 133 collected by Alvin and the samples were then studied extensively. Each sample had been characterized by composition, sorted by occurrence and distribution of pheneocrysts so that possible crystal fractionation processes can be determined, and then sorted by morphology and stratigraphic relationships to be compared to the model of magma evolution and eruption. (Stakes et al. 1984)

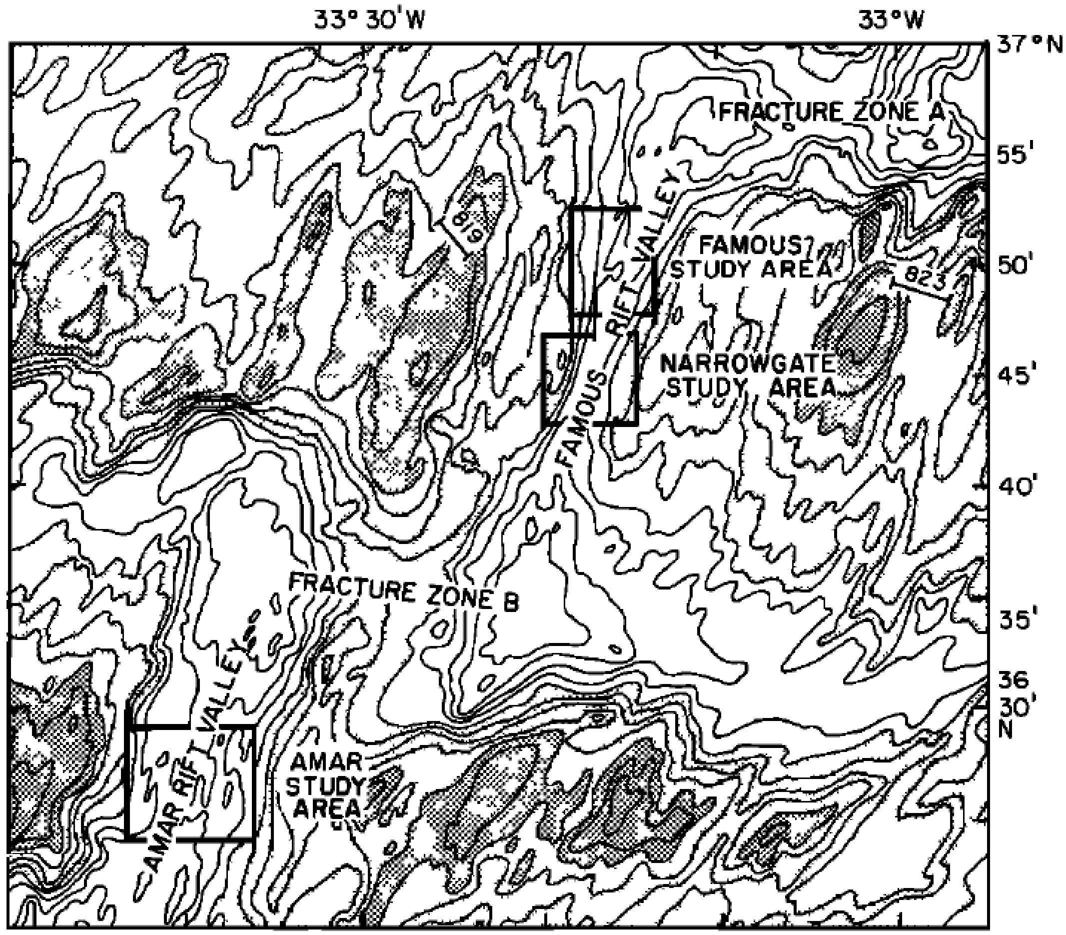

Figure 1. (Stakes et al. 1984) This index map shows the location of the 1978 AMAR and NARROWGATE study areas and the 1977 FAMOUS study region. Compared to my study area on figure (2). For the purpose of showing the locations of samples.

This study focuses on the FAMOUS segment near 36°44’N-36°52’N on the Mid-Atlantic Ridge (MAR). The axial valley of the MAR from 36° to 37°N was sampled by submersible during the FAMOUS and AMAR projects.

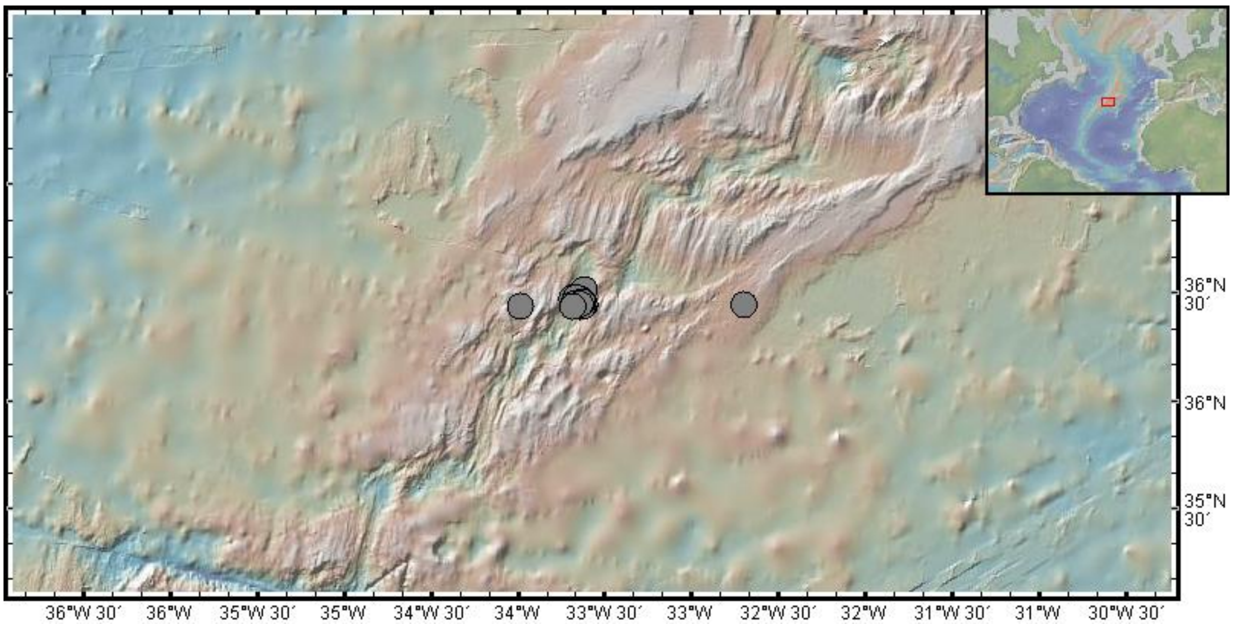

Figure 2. FAMOUS region coordinates between latitudes 36° 44' - 36° 52’, longitudes 30° 70'-33° 99'.

The FAMOUS-AMAR region which is offset by a fracture zone B is between two areas of the MAR, Azores platform at 38°-40°N and Oceanographer Fracture Zone at ~ 35°N. The FAMOUS valley extends from fracture zone A in the north to fracture zone B in the south (Figure 1). The NARROWGATE region is half way between these fracture zones where the FAMOUS valley thins to less than 3 km wide and is V-shaped (Stakes et al. 1984).

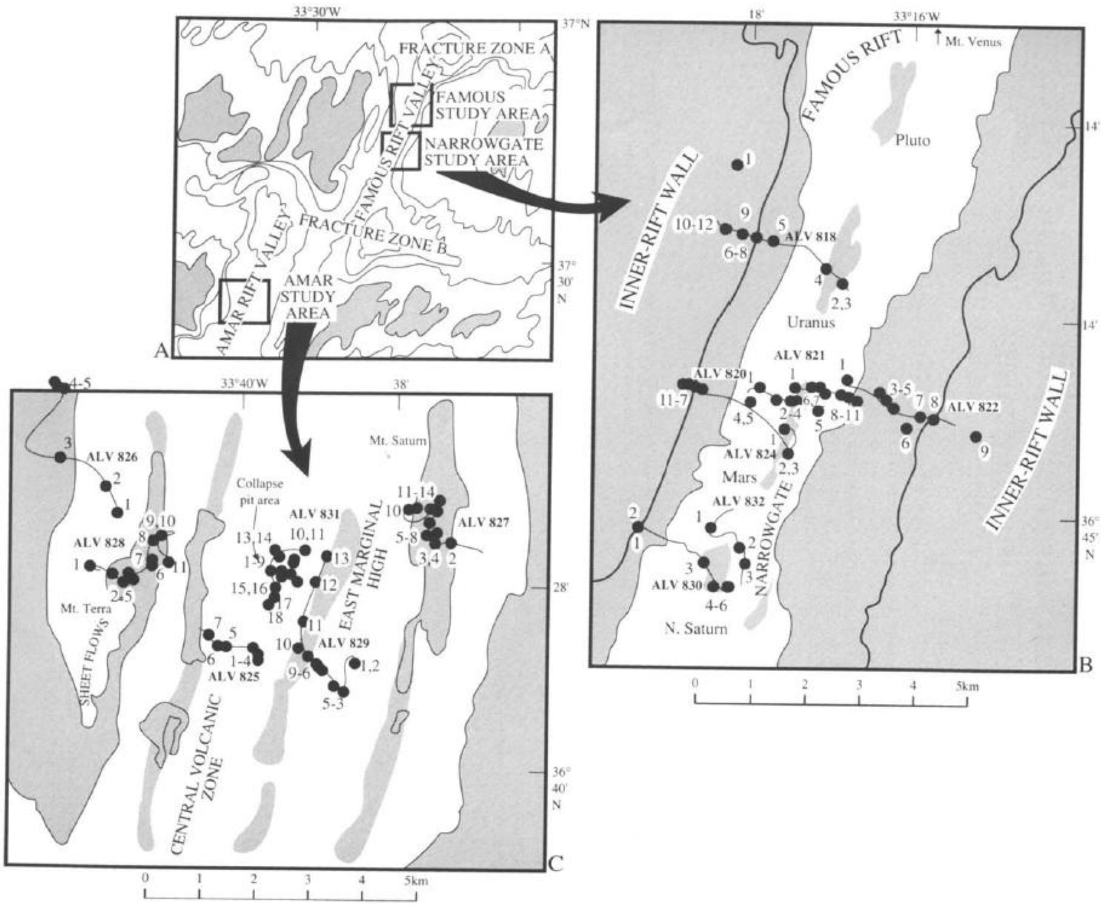

Figure 3. Image from Frey et al. (1993). FAMOUS, NARROWGATE, and AMAR study areas of the Mid-Atlantic Ridge.

The age and succession of volcanism in the rift valley was estimated by Storzer et al. (1976) through fission track sample analyses. The samples were retrieved from the rift valley inner floor of the FAMOUS region. They estimated the age to be approximately less than 3,000-21,000 ±6,000 years old. The youngest volcanoes form a narrow zone of oceanic crust which is only about 1 to 2 kilometers wide, compared to the size of the plates, which are thousands of kilometers across (Frey et al. 1993). The FAMOUS geological effort showed that the rift valley is created by large faults that break through the newly formed oceanic crust and that active volcanoes are abundant along the rift valley floor.

Stakes et al. (1984) determined that typical of MORB (mid-ocean ridge basalt), lavas from the AMAR and FAMOUS valleys are olivine and quartz normative tholeiites. Within each valley, at a given MgO content, the lavas vary significantly in TiO_2 and K_20 abundance. This result provides evidence for multiple parental magma compositions. In the northern FAMOUS valley the older, higher MgO content samples of basalts form the young volcanic cones in the center of the valley. Yet, in the AMAR and NARROWGATE valleys the most evolved samples are in the central part of the valley.

Methods

There are many petrologic methods that can be used to determine the pressure of partial crystallization which later be converted to depth. The method used relies on the composition of quenched magma (glass) compared to the compositions of liquids lying along pressure dependent phase boundaries. The pressure of partial crystallization can be related using equations that describe the location of these liquid compositions on the pressure dependent coetectic.

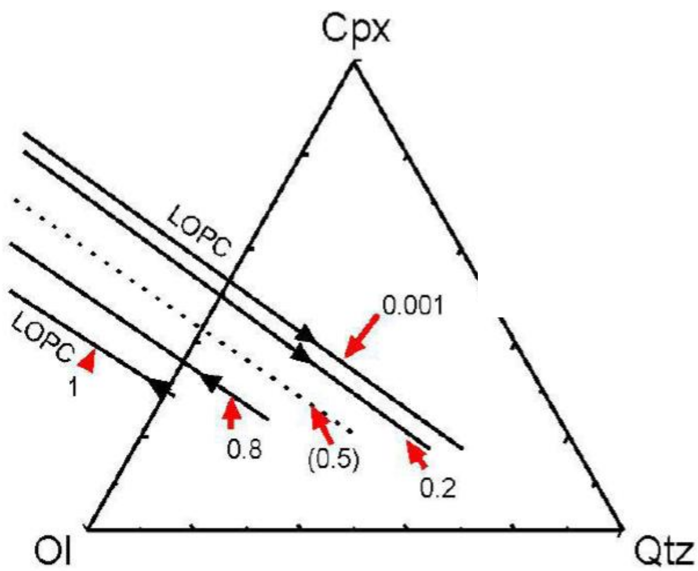

Figure 4. The olivine, plagioclase, clinopyroxene coetectic. Taken from Kelley and Barton. (2008)

The results are based on the chemical equilibrium relationship between the liquid portion of the magma in a chamber in the crust and the solid minerals that are forming from it. The chemical composition of the melt changes systematically with changes in pressure (Kelley and Barton. 2008). Most basalts crystallize olivine, plagioclase, and clinopyroxene prior to eruption. Thus, the pressure at which the liquid is saturated with these mineral phases prior to the eruption can be determined using the chemical analysis of the forms when the magma quenched. The pressures are directly related to a depth below the Earth's surface that represents the depth at which that magma had last paused long enough during ascent to achieve equilibrium with this mineral assemblage. The equation relating pressure (P) to depth (z) is

$P=\rho gz$. Where ρ is the crustal density of basalt (2900kg/$m^{3)}$, and g is the acceleration due to gravity (9.8m/s^2).

Data

The glasses analyses were obtained from the petdb.org website. Pressures were calculated for these samples as described in the methods section. Any samples with compositions inconsistent with crystallization of olivine, plagioclase, and clinopyroxene were omitted. This is possible because the variations of liquid compositions resulting from crystallization of olivine, plagioclase, and clinopyroxene have been established from experimental work (Kelley and Barton. 2008). In addition results for samples that generated calculated pressures with excessive errors were also eliminated. Kelley and Barton. (2008) determined that the 1-standard deviation errors for calculated pressures should be less than 130 MPa. Samples that projected calculated pressures with uncertainties greater than 130 MPa were filtered out of the data set.

Results

Pressures calculated for 65 samples range between 0 -228.5 MPa. The depths calculated range from 0-8.04km. This indicates that the FAMOUS magmas evolve over a range of depths in the crust. We also found that magma mixing and crystal-melt fractionation were the major processes controlling the compositions of FAMOUS glasses. The average pressure is 40.39MPa which suggests an average depth of 1.42km. In figures 5a, 5b, 5c, and 5d our final result shows nothing is irregular.

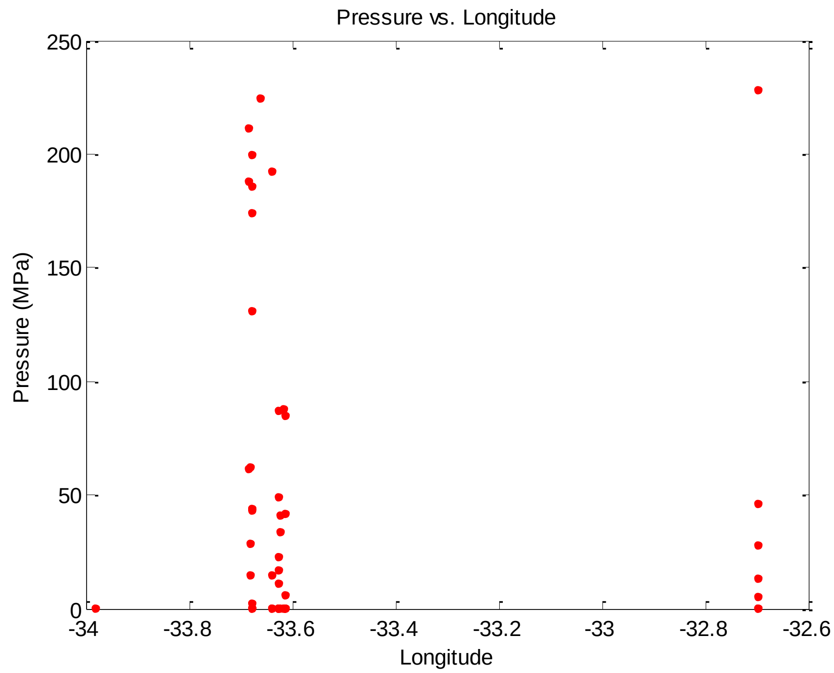

Figure 5a. Pressure vs. Longitude

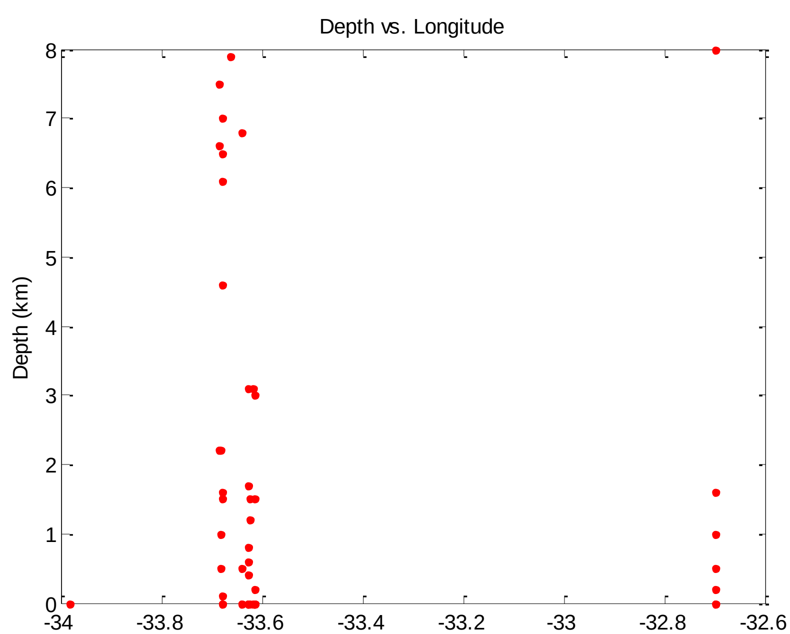

Figure 5b. Depth vs. Longitude

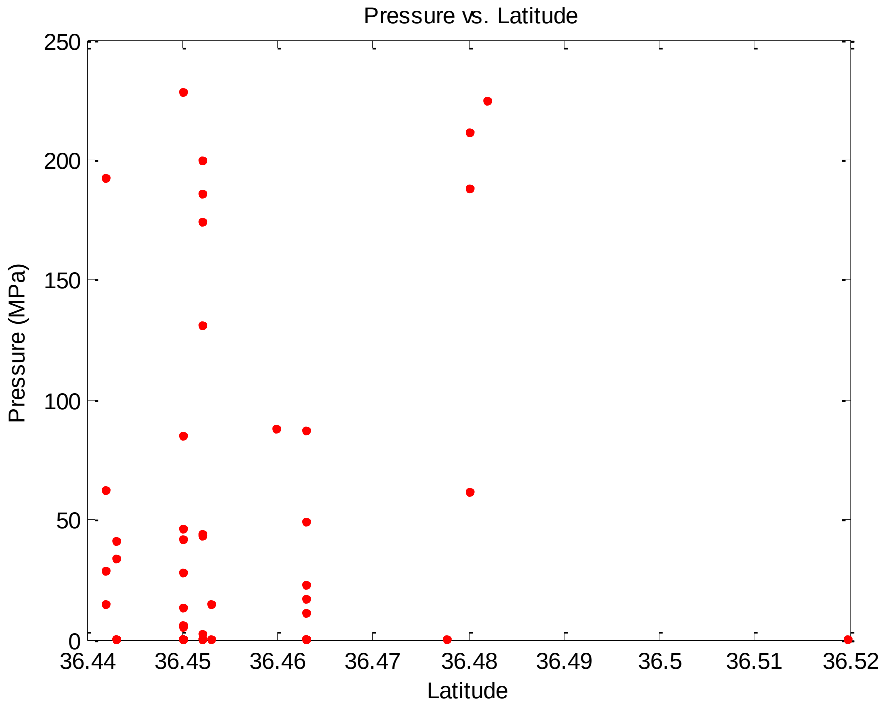

Figure 5c. Pressure vs. Latitude

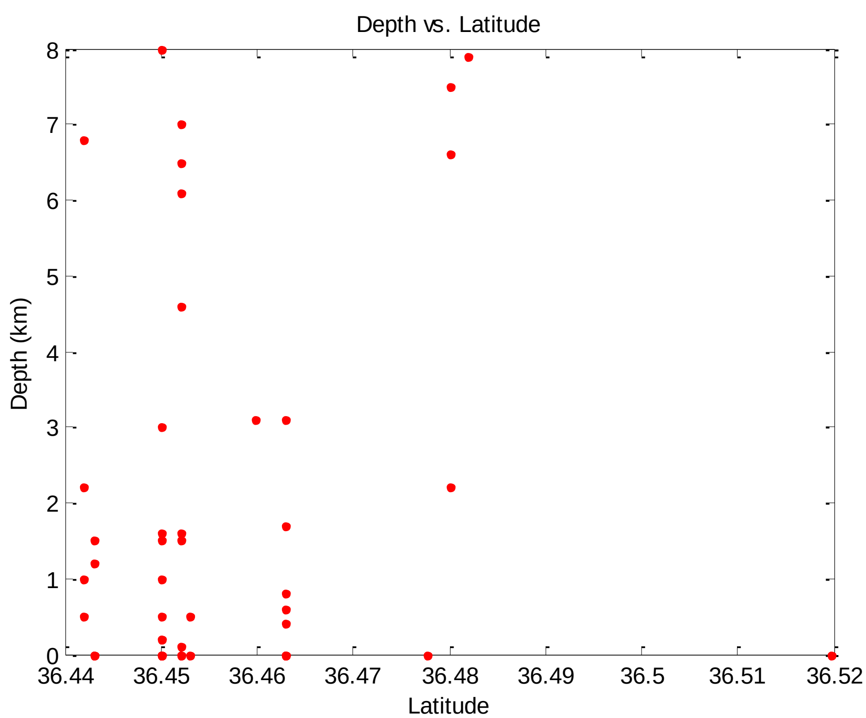

Figure 5d. Depth vs. Latitude

Discussion

Crystallization takes place in boundary layers or solidification zones at the margins of magma chambers. While this zone solidifies, residual melt is returned to and combined with the main magma body which is not crystallizing. If the residual melt from the boundary layer reflects a large amount of crystallization some phases that crystallized in the solidification zone are not in a melt in the main magma body. Therefore the mixed magma can demonstrate compositional control by a phase such clinopyroxene that is not a liquid phase and is absent as a phenocryst phase. (Frey et al. 1993) The calculated pressures exemplify the pressure of crystallization only for glasses that represent liquids lying along the olivine, plagioclase, clinopyroxene coetectic. The results suggest that magma chambers beneath the sub-areal volcanoes are located at depths of about 1.42km. The results obtained in this study suggest that the chambers are positioned at moderately shallow depths implying that a large shallow heat sources are accessible and can be tapped for geothermal energy.

The average depth of crystallization of magmas in this study of the FAMOUS region which is 1.42km doesn't necessarily disagree with the model proposed by Stakes et al. (1984) which illustrates depths of magma chambers ranging from 3-6km. There is a margin of error to take into account of 3km, also the water column has not been factored in.

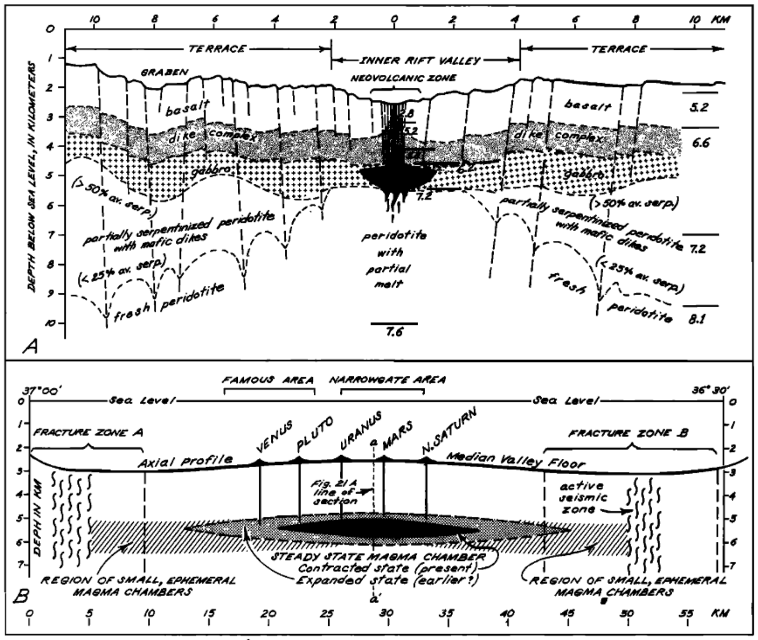

Figure 6. Propsosed magma chamber. Taken from Stakes et al. (1984)

Conclusion

Pressures calculated from 65 glasses in the FAMOUS region indicate crystallization range from 0 to 228.5MPa, equivalent to depths of 0-8.04 km but averaging a depth of 1.42km. The method to calculate pressures of crystallization of melts lying along the olivine, plagioclase, clinopyroxene coetectic based on the procedure described by Yang et al. (1996) indicates that the results are accurate to ±110MPa (1б) and are precise to 80MPa (1 б). Magma chamber depths estimated at 1.42km below see floor will most likely agree with Stakes et al. (1984) model after factoring in the water column.

References

Baker, E.T., 2009, Relationships between hydrothermal activity and axial magma chamber distribution, depth, and melt content: Geochemistry, Geophysics, Geosystems – G^3,v.10, doi: 10.1029/2009GC002424.

Folch, A., and Marti, J., 2009, Time-dependent chamber and vent conditions during explosive caldera-forming eruptions: Earth and Planetary Science Letters, v. 280, p. 246-253, doi: 10.1016/j.epsl.2009.01.035.

Frey, F.A., Walker, N., Stakes, D., Hart, S.R., and Nielsen, R., 1993, Geochemical characteristics of basaltic glasses from the AMAR and FAMOUS axial valleys, Mid-Atlantic Ridge (36 degrees -37 degrees N); petrogenetic implications: Earth and Planetary Science Letters, v. 115, p. 117-136.

Gale, A., Escrig, S., Gier, E.J., Langmuir, C.H., and Goldstein, S.L., 2011, Enriched basalts at segment centers; the Lucky Strike (37 degrees 17'N) and Menez Gwen (37 degrees 50'N) segments of the Mid-Atlantic Ridge: Geochemistry, Geophysics, Geosystems – G^3, v. 12, doi: 10.1029/2010GC003446.

Hekinian, R., Moore, J.G., and Bryan, W.B., 1976, Volcanic rocks and processes of the Mid-Atlantic Ridge rift valley near 36 degrees 49'N: Contributions to Mineralogy and Petrology, v. 58, p. 83-110.

Kelley, D.F., and Barton, M., 2005, Thickness, composition and physical properties of crust in Iceland's neovolcanic zone: EOS, Transactions, American Geophysical Union, v. 86, Abstract no. V13E-0591.

Kelley, D.F., Kabbes, J.E., and Barton, M., 2008, Magma chamber depths at Kverkfjoll volcanic system, Iceland and connections to recent dyke injection at Mount Upptyppingar, Iceland: EOS, Transactions, American Geophysical Union, v. 89, Abstract no. V33D-2244.

Kinzler, R.J., and Grove, T.L., 1992, Primary magmas of mid-ocean ridge basalts; 1, Experiments and methods: Journal of Geophysical Research, v. 97, p. 6885-6906, doi: 10.1029/91JB02840.

Langmuir, C., Humphris, S., Fornari, D., Van Dover, C., Von Damm, K.L., Tivey, M.K., Colodner, D., Charlou, J.L., Desonie, D., Wilson, C., Fouquet, Y., Klinkhammer, G., and Bougault, H., 1997, Hydrothermal vents near a mantle hot spot; the Lucky Strike vent field at 37 degrees N on the Mid-Atlantic Ridge: Earth and Planetary Science Letters, v. 148, p. 69-91.

Langmuir, C.H., Fornari, D., Colodner, D., Charlou, J.L., Costa, I., Desbruyeres, D., Desonie, D., Emerson, T., Fiala-Medioni, A., Fouquet, Y., Humphris, S., Saldanha, L., Sours-Page, R., Thatcher, M., Tivey, M., Van Dover, C., Von Damm, K., Wiese, K., and Wilson, C., 1993, Geological setting and characteristics of the Lucky Strike vent field at 37 degrees 17'N on the

Mid-Atlantic Ridge: EOS, Transactions, American Geophysical Union, v. 74, p. 99.

Laubier, M., and Langmuir, C.H., 2008, Primitive melt inclusions from multiple samples from the FAMOUS Zone; insights into the mantle melting column and the fractionation processes: EOS, Transactions, American Geophysical Union, v. 89, Abstract no. V13F-03.

Laubier, M., Gate, A., and Langmuir, C.H., 2012, Melting and crustal process at the FAMOUS segment (Mid-Atlantic Ridge); new insights from olivine-hosted melt inclusions from multiple samples: Journal of Petrology, v. 53, p. 665-698, doi: 10.1093/petrlogy/egr075.

Laubier, M., Schiano, P., Doucelance, R., Ottolini, L., and Laporte, D., 2007, Olivine-hosted melt inclusions and melting processes beneath the FAMOUS zone (Mid-Atlantic Ridge): Chemical Geology, v. 240, p. 129-150, doi: 10.1016/j.chemgeo.2007.02.002.

le Roex, A.P., Frey, F.A., and Richardson, S.H., 1996, Petrogenesis of lavas from the AMAR Valley and Narrowgate region of the FAMOUS Valley, 36 degrees 37 degrees N on the Mid-Atlantic Ridge: Contributions to Mineralogy and Petrology, v. 124, p. 167-184, doi: 10.1007/s004100050183.

Nabelek, P.J., and Langmuir, C.H., 1986, The significance of unusual zoning in olivines from FAMOUS area basalt 527-1-1: Contributions to Mineralogy and Petrology, v. 93, p. 1-8.

Pan, Y., and Batiza, R., 2002, Mid-ocean ridge magma chamber processes; constraints from olivine zonation in lavas from the East Pacific Rise at 9 degrees 30'N and 10 degrees 30'N: Journal of Geophysical Research, v. 107, doi: 10.1029/2000JB000435.

Rubin, K.H., and Sinton, J.M., 2007, Inferences on mid-ocean ridge thermal and magmatic structure from MORB compositions: Earth and Planetary Science Letters, v. 260, p. 257-276, doi: 10.1016/j.epsl.2007.05.035.

Scott, J., Kelley, D.F., Barton, M., and Panero, W., 2008, Petrological constraints on magma chamber depths, magma plumbing systems, and crustal thickness along the Reykjanes Ridge, North Atlantic: EOS, Transactions, American Geophysical Union, v. 89, Abstract no. V33D-2245.

Seher, T., Crawford, W., and Singh, S., 2007, Crustal thickness variations due to deep faulting and the velocity structure of the Lucky Strike segment (37N Mid-Atlantic Ridge): EOS, Transactions, American Geophysical Union, v. 88, Abstract no. S23A-1119.

Seher, T., Crawford, W.C., Singh, S.C., Cannat, M., Combier, V., and Dusunur, D., 2010, Crustal velocity structure of the Lucky Strike segment of the Mid-

Atlantic Ridge at 37 degrees N from seismic refraction measurements: Journal of Geophysical Research, v. 115, doi: 10.1029/2009JB006650.

Seher, T., Singh, S.C., Crawford, W.C., and Escartin, J., 2010, Upper crustal velocity structure beneath the central Lucky Strike Segment from seismic refraction measurements: Geochemistry, Geophysics, Geosystems - G^3 v. 11, doi: 10.1029/2009GC002894.

Singh, S.C., Crawford, W.C., Carton, H., Sehr, T., Combier, V., Cannat, M., Canales, J.P., Dusunur, D., Escartin, J., and Miranda, J.M., 2006, Discovery of a magma chamber and faults beneath a Mid-Atlantic Ridge hydrothermal field: Nature [London], v. 442, p. 1029-1032, doi: 10.1038/nature05105.

Stakes, D.S., Shervais, J.W., and Hopson, C.A., 1984, The volcanic-tectonic cycle of the FAMOUS and AMAR valleys, Mid-Atlantic Ridge (36 degrees 47'N); evidence from basalt glass and phenocryst compositional variations for a steady state magma chamber beneath the valley midsections, AMAR 3: Journal of Geophysical Research, v. 89, p. 6995-7028, doi: 10.1029/JB089iB08p06995.

Stewart, M.A., Klein, E.M., and Karson, J.A., 2002, Geochemistry of dikes and lavas from the north wall of the Hess Deep Rift; insights into the four-dimensional character of crustal construction at fast spreading mid-ocean ridges: Journal of Geophysical Research, v. 107, doi: 10.1029/2001JB000545.

Storzer, D., and Selo, M., 1976, Uranium contents and fission track ages of some basalts from the FAMOUS area: Bulletin De La Societe Geologique De France, v. 18, p. 807-810.

Thy, P., 1991, High and low pressure phase equilibria of a mildly alkalic lava from the 1965 Surtsey eruption; experimental results: Lithos, v. 26, p. 223-243, doi: 10.1016/0024-4937(91)90030-O.

Walker, D., Shibata, T., and DeLong, S.E., 1979, Abyssal tholeiites from the Oceanographer fracture zone; II, Phase equilibria and mixing: Contributions to Mineralogy and Petrology, v. 70, p. 111-125.

Yang, H.J., Kinzler, R.J., and Grove, T.L., 1996, Experiments and models of anhydrous, basaltic olivine-plagioclase-augite saturated melts from 0.001 to 10 kbar: Contributions to Mineralogy and Petrology, v. 124, p. 1-18, doi: 10.1007/s004100050169.

Yucheng, P., and Batiza, R., 2003, Magmatic processes under mid-ocean ridges; a detailed mineralogic study of lavas from East Pacific Rise 9 degrees 30'N, 10 degrees 30'N, and 11 degrees 20'N: Geochemistry, Geophysics, Geosystems - G^3 v. 4, doi: 10.1029/2002GC000309.